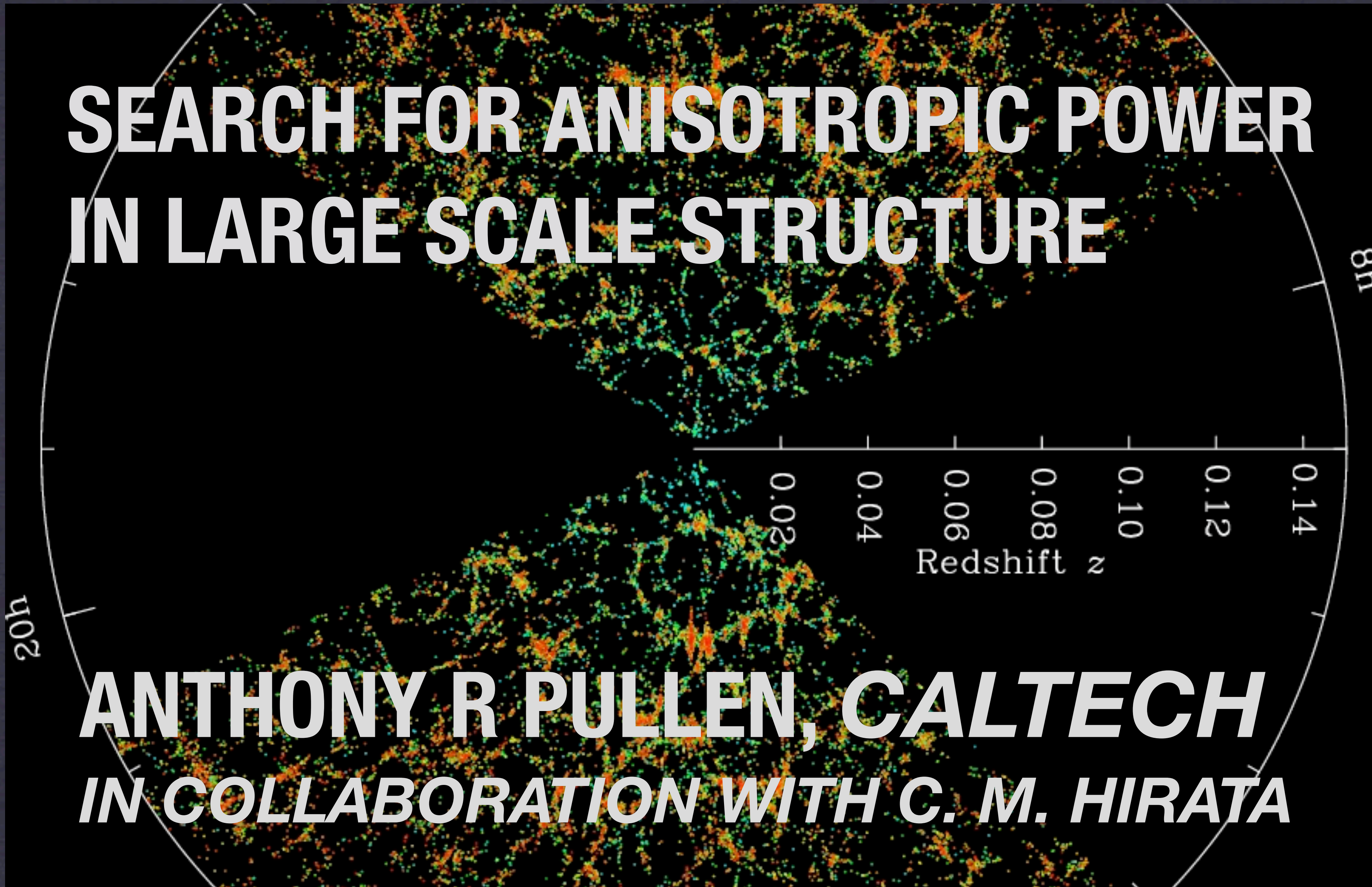
SEARCH FOR ANISOTROPIC POWER IN LARGE SCALE STRUCTURE



ANTHONY R PULLEN, *CALTECH*

IN COLLABORATION WITH C. M. HIRATA

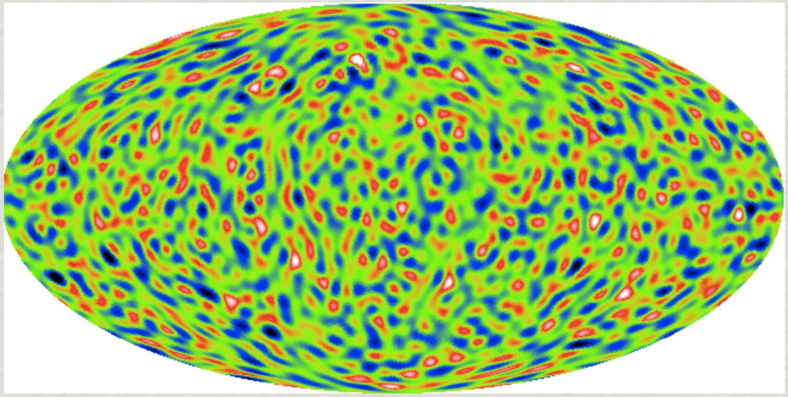
"Non-detection of a statistically anisotropic power spectrum in large scale structure" JCAP 05, 27 (2010)

Outline

* Introduction
* Previous Work
* Model/Data
* Quadrupole Estimators
* Results/Systematics
* Luminous Red Galaxies (LRG) vs CMB Results
* Summary

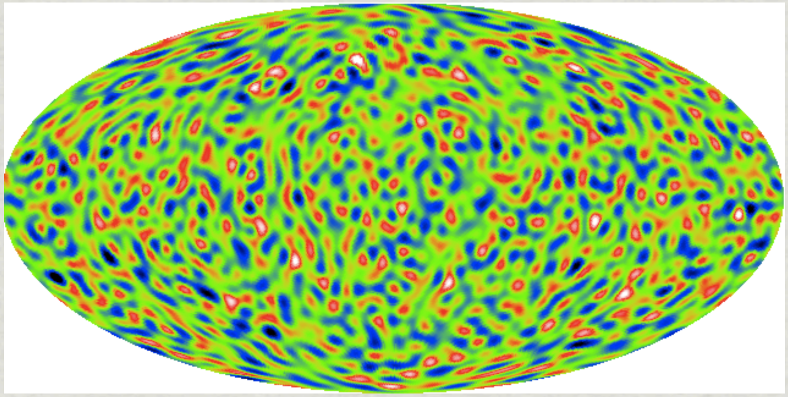
Introduction

- Statistical Isotropy (SI) - variance of perturbations is *direction-independent*
- Standard Cosmology
- Template for analysis

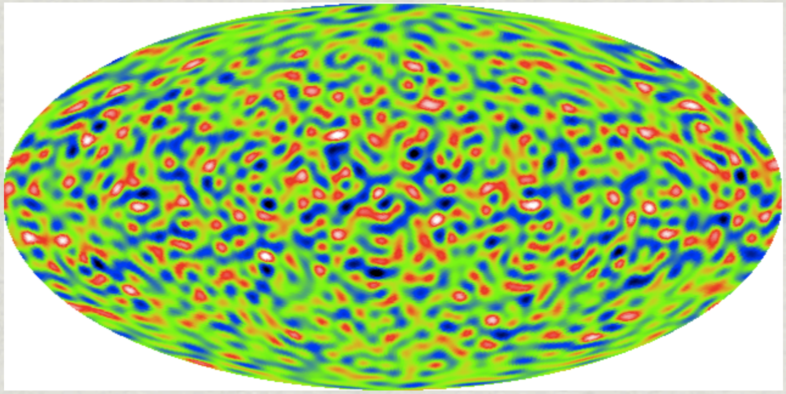


Introduction

- Statistical Anisotropy (SA) - variance of perturbations *varies with direction*
- Nonstandard Cosmology - many possible sources



Statistical Isotropy



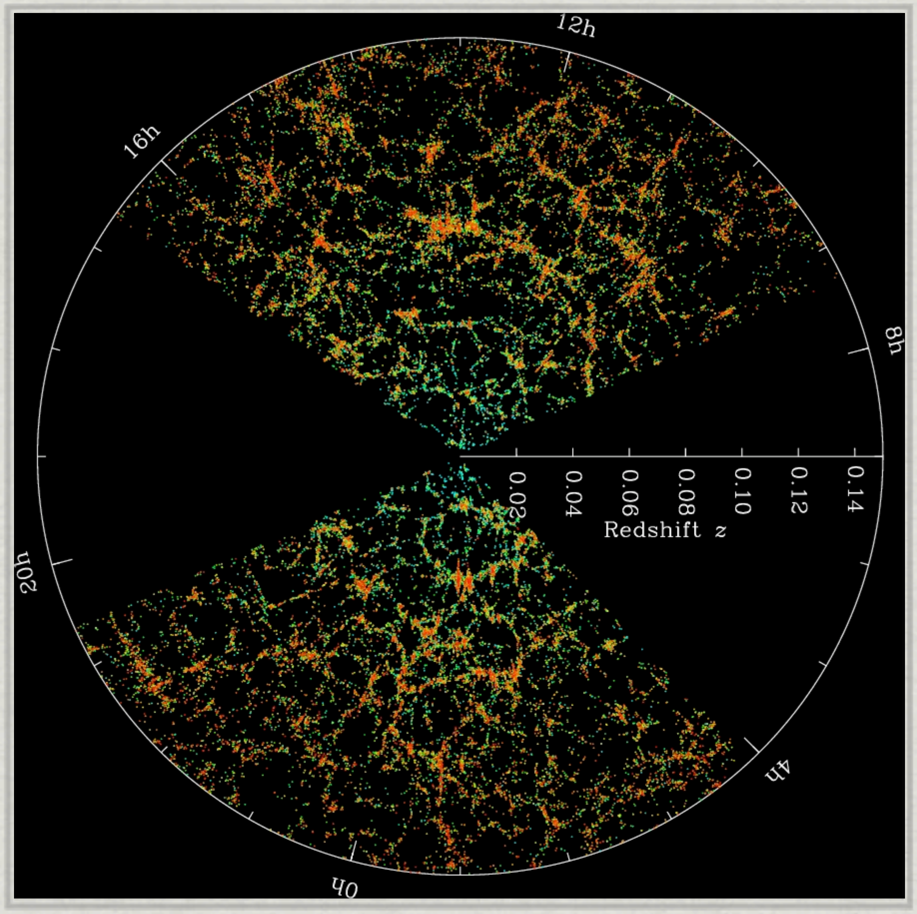
Quadrupolar Asymmetry

Previous Work

- Searches for Statistical Anisotropy in the CMB
- Quadrupole/Octopole Alignment - behaves like globally random anisotropy
- Dipole Asymmetry - not significant when marginalized over choice of dipole cutoff
- Quadrupolar Anisotropy - alignment with ecliptic suggests systematic effect, e.g. beam asymmetry

Model/Data

- Galaxy surveys
- Complement CMB probes of SI
- Probe anisotropy at low redshift
- Transcend limits of CMB foregrounds



SDSS DR7 Image

Model/Data

$$\langle \delta(\mathbf{k}) \delta^*(\mathbf{k}') \rangle = (2\pi)^3 \delta_D(\mathbf{k} - \mathbf{k}') P(k)$$

gaussian
isotropic

$$\boxed{\langle \delta(\mathbf{k}) \delta^*(\mathbf{k}') \rangle = (2\pi)^3 \delta_D(\mathbf{k} - \mathbf{k}') P(\mathbf{k})}$$

gaussian
anisotropic

$$P(\mathbf{k}) = \bar{P}(k) \left[1 + \sum_{LM} g_{LM}(k) R_{LM}(\hat{\mathbf{k}}) \right]$$

isotropically averaged

multipolar anisotropy moment

real-valued spherical harmonics

Model/Data

- Our model: scale-invariant quadrupolar anisotropy with linear bias

$$\bar{P}_g(k) = b_g^2 \bar{P}(k)$$

$$P(\mathbf{k}) = \bar{P}(k) \left[1 + \sum_{M=-2}^{2} g_{2M} R_{2M}(\hat{\mathbf{k}}) \right]$$

- First-order correction (only *even L* allowed)

- Motivated by Ackerman, Carroll, Wise (ACW) inflation model - *Ackerman et al. 2007*

Model/Data

- Angular power spectra used in anisotropy estimate
- Luminous red galaxies (LRGs) used as tracers
- 8 photometric z-slices with $\Delta z = 0.05$
- 1.4 million pixels, 12 sqr arcmin each
- Prior spectra calculated using fiducial values

Quadrupole Estimators

Project $\delta_g(\mathbf{x})$ to z-slice and find covariance

$$\delta_g(\hat{\mathbf{n}}) = \int \mathrm{d}\chi f(\chi)\delta_g(\mathbf{x} = \chi\hat{\mathbf{n}})$$

$$\begin{aligned} C_g(\hat{\mathbf{n}}, \hat{\mathbf{n}}')|_{\mathrm{SI}} &= C_g(\theta) \\ &= \sum_l \frac{2l+1}{4\pi} C_{g,l} P_l(\cos\theta) \end{aligned}$$

angular power spectrum

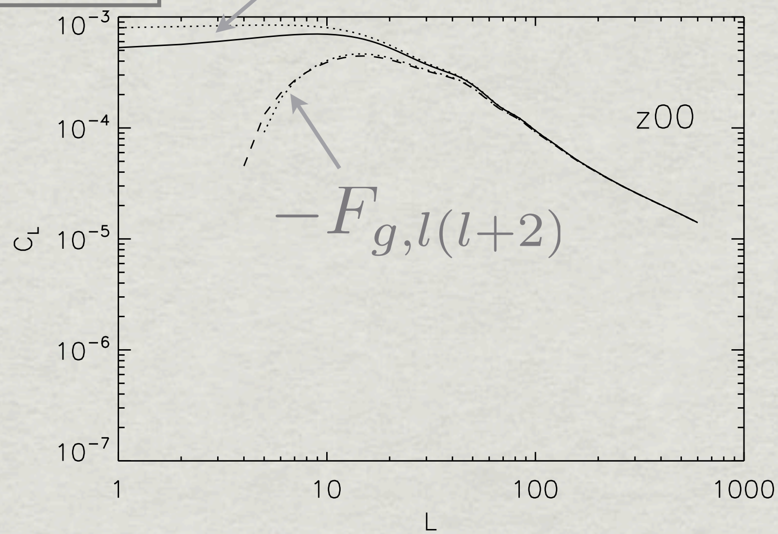
Quadrupole Estimators

$$C_g(\hat{\mathbf{n}},\hat{\mathbf{n}}')\big|_{\substack{\mathrm{SA}\\ g_{2M}\neq 0}} = \sum_{M=-2}^{2}\sum_{lml'm'} g_{2M} F_{g,ll'} X^{2M}_{lml'm'} R_{lm}(\hat{\mathbf{n}}) R_{l'm'}(\hat{\mathbf{n}}')$$

generalized angular power spectrum

3 harmonic couplings

$C_{g,l}$



$-F_{g,l(l+2)}$

Quadrupole Estimators

- Goal: Estimate $C_{g,l}$ and g_{2M} at all redshift slices
- Parameters: $\tilde{C}_n$ and g_{2M}

$$C_{g,l} = \sum_{n=1}^{18} \tilde{C}_n \eta_l^n$$

- Estimator: $\hat{\mathbf{p}} = \mathbf{F}^{-1}\mathbf{q}$

Parameter vector

Fisher matrix

Quad vector

$$\mathbf{C} = \sum_{i=1}^{N_t} p_i \mathbf{C}_{,i}$$

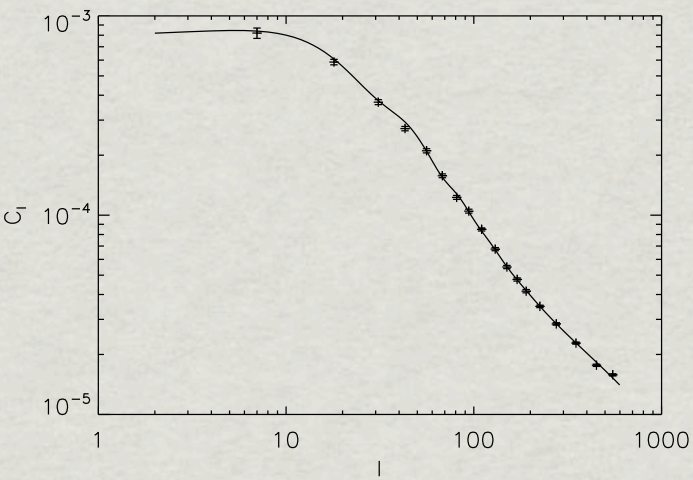
- Noise: Poissonian ($1/n_{gal}$)

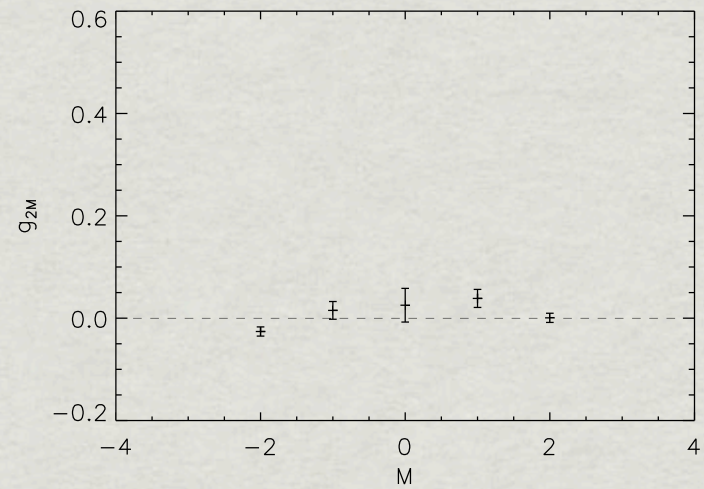
Quadrupole Estimators

- Monte Carlo simulations to test estimator
- 50 simulations of $\delta_{g,lm}$ for z-slice z00 (z=[0.2,0.25])
- Test with SI: $g_{2M} = 0\,, \forall M$
- Test with SA: use $g_{20} = 0.5$
- Noise: $C^N = 1/n_{\rm gal} \simeq 6.7$

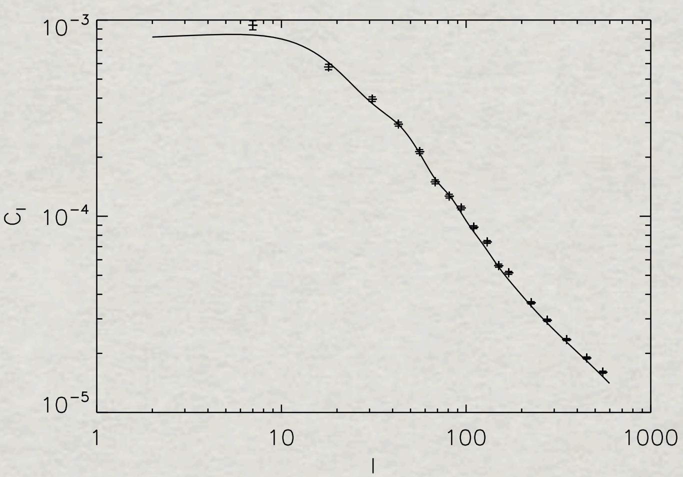
Quadrupole Estimators

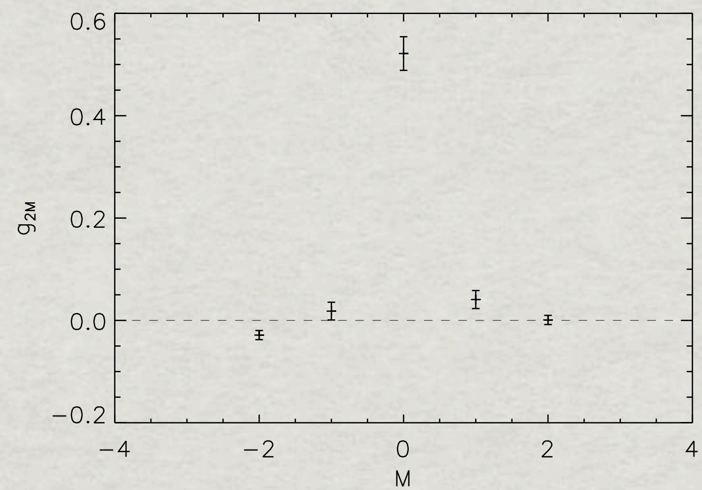
$g_{20} = 0$



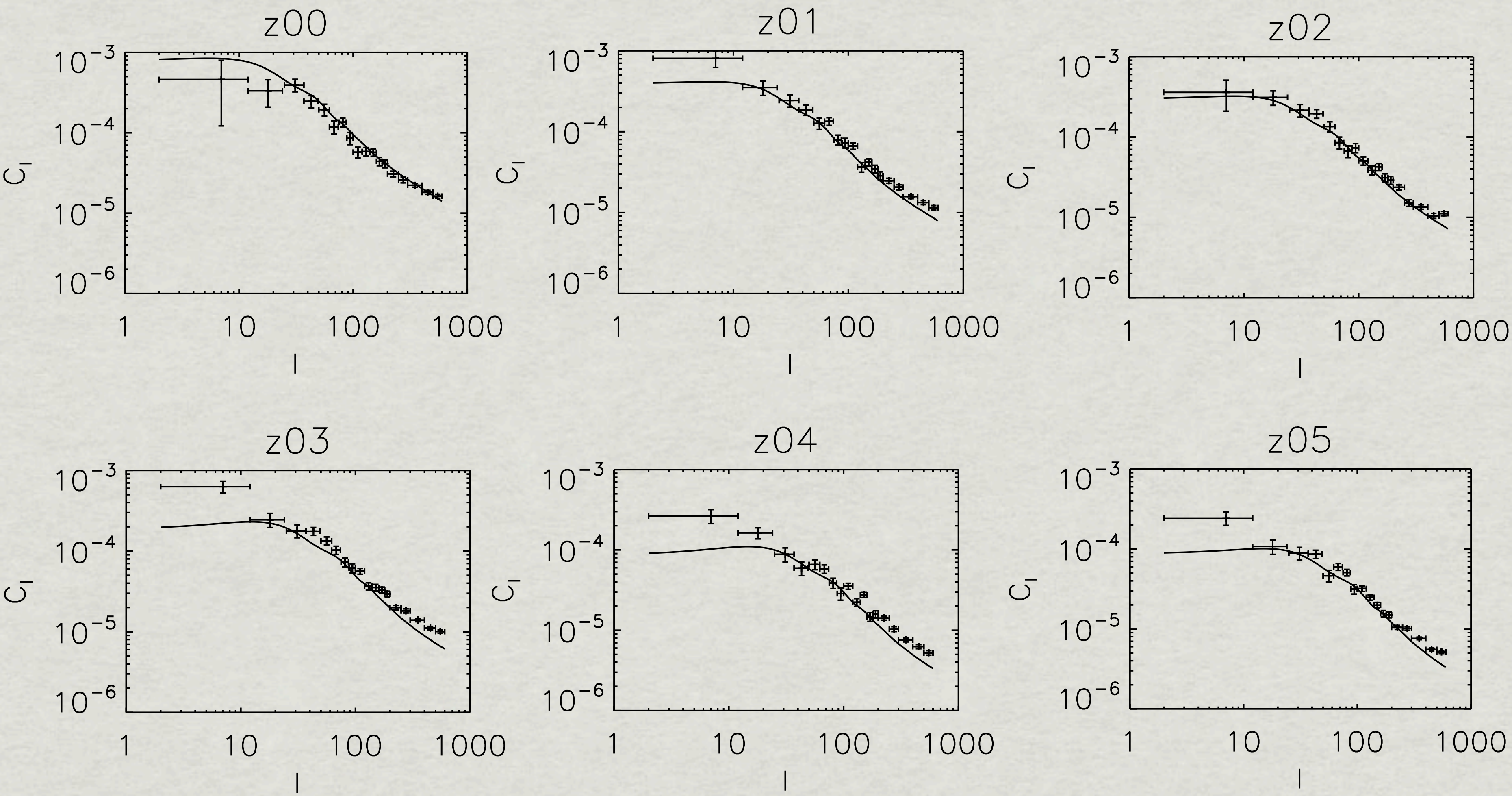


$g_{20} = 0.5$

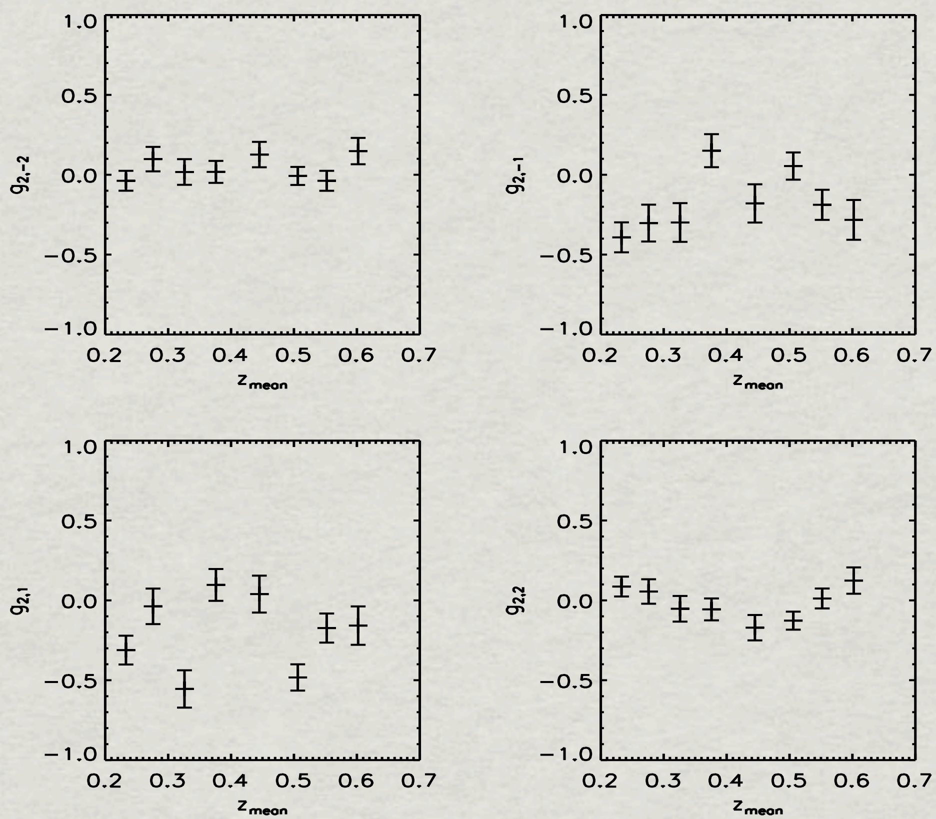




Results/Systematics



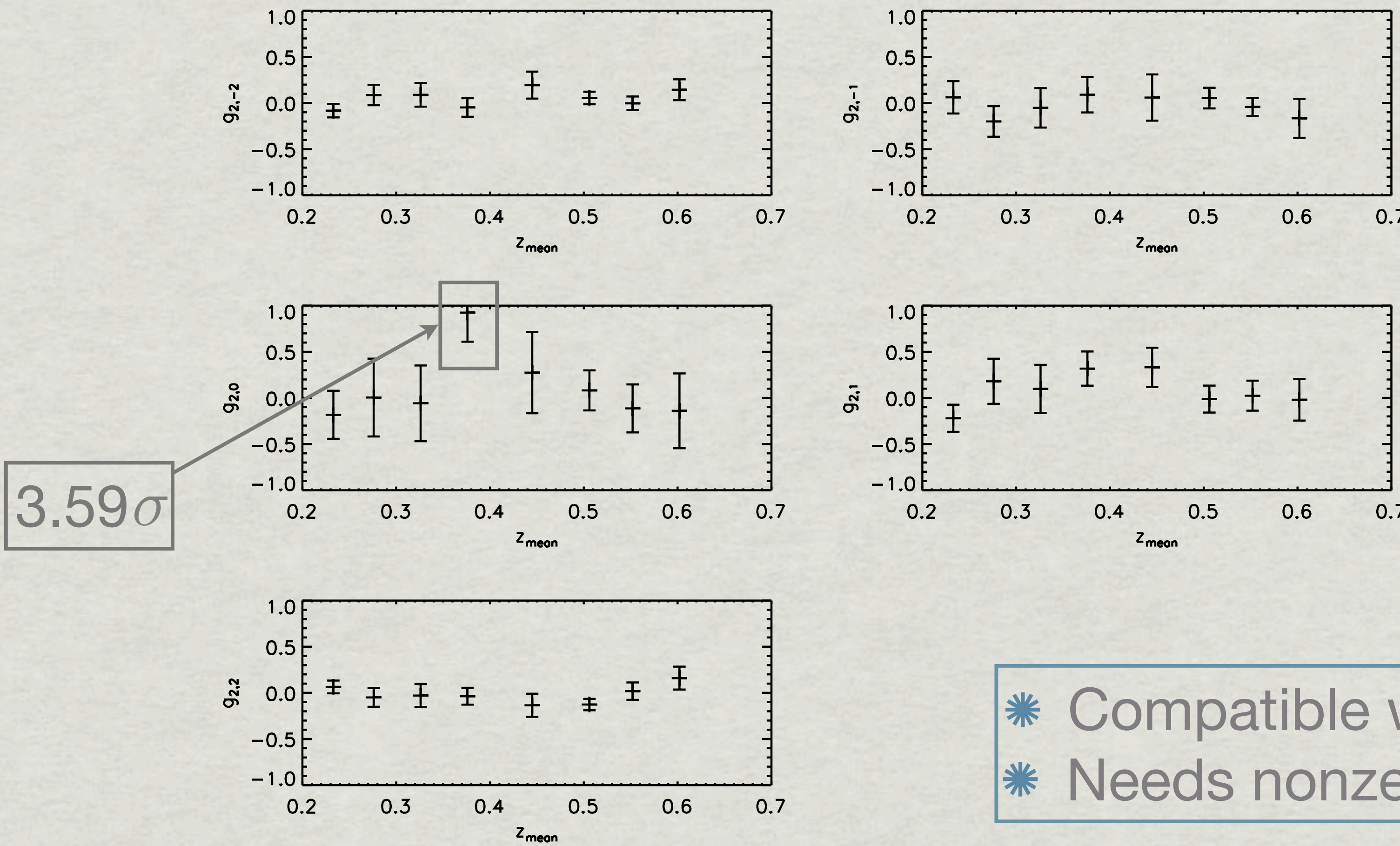
Results/Systematics



- Incompatible with zero
- Varies with redshift
- Fix with modulation

$$\delta'(\hat{\mathbf{n}}) = \left[1 + \sum_{M=-2}^{2} h_{2M} R_{2M}(\hat{\mathbf{n}})\right] \delta(\hat{\mathbf{n}})$$

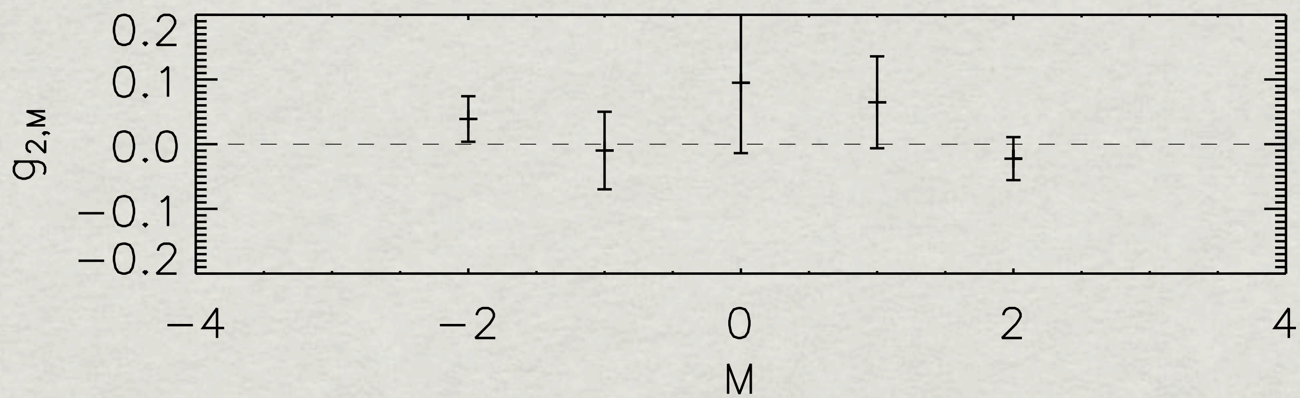
Results/Systematics



- Compatible with zero
- Needs nonzero h_{2M}

Results/Systematics

Minimum Variance Estimator



- Error estimates from N-body simulations
- Includes z-slice covariances and nongaussianity effects
- $C_{M,M'}$ were also calculated

LRG vs CMB Results

- Groeneboom *et al.* investigate ACW model using WMAP

$$P(\mathbf{k}) = P(k)[1 + g_*(\hat{\mathbf{k}} \cdot \hat{\mathbf{n}})^2]$$

amplitude

preferred axis

$$g_{2M} = \frac{8\pi}{15} g_* R_{2M}(\hat{\mathbf{n}})$$

Not directly invertible

LRG vs CMB Results

- Construct estimator for g_*^{LRG}

$$\hat{g}_* = \frac{15}{8\pi} \frac{\sum_{MM'} [C^{-1}]_{MM'} \hat{g}_{2M} R_{2M'}(\hat{\mathbf{n}})}{\sum_{MM'} [C^{-1}]_{MM'} R_{2M}(\hat{\mathbf{n}}) R_{2M'}(\hat{\mathbf{n}})}$$

- Must choose a preferred direction for estimator

LRG vs CMB Results

$\hat{\mathbf{n}}$	**CMB**	**LRG**
WMAP W band $(l,b) = (94^\circ, 26^\circ)$	$g_*^{\mathrm{CMB}} = 0.29 \pm 0.031$	$g_*^{\mathrm{LRG}} = 0.006 \pm 0.036$
WMAP V band $(l,b) = (94^\circ, 27^\circ)$	$g_*^{\mathrm{CMB}} = 0.14 \pm 0.034$	$g_*^{\mathrm{LRG}} = 0.007 \pm 0.037$

Asymmetry in direction of the Ecliptic

LRG vs CMB Results

- WMAP result could be due to beam asymmetries
- Hanson and Lewis show effect could produce result; disputed by Groeneboom *et al.*
- WMAP team hopes to complete full simulation of beam asymmetry effect
- Already accounted for in power spectrum estimator

LRG vs CMB Results

- Can different values for g_{2M} be due to *k*-variance?
- Variance with number of *e*-folds: $g_{2M} \propto \ln k$
- Calculate $k_{\rm eff}$ that makes *k*-invariant estimator correct
- $k_{\rm eff}$: 0.020 Mpc^{-1} (CMB), 0.15 Mpc^{-1} (LRG)
- Differ by 2 *e*-folds; too small for 100x difference

LRG vs CMB Results

- Construct Bayesian estimator with $\hat{\mathbf{n}}$ marginalized

$$\mathcal{L}(g_*) = \int \exp\left\{-\frac{1}{2}\sum_{MM'}[C^{-1}]_{MM'}\left[\hat{g}_{2M} - \frac{8\pi}{15}g_* R_{2M}(\hat{\mathbf{n}})\right] \times \left[\hat{g}_{2M'} - \frac{8\pi}{15}g_* R_{2M'}(\hat{\mathbf{n}})\right]\right\} d^2\hat{\mathbf{n}}$$

- Assume uniform priors
- 68% C.L. : $-0.12 < g_* < +0.10$
- 95% C.L. : $-0.41 < g_* < +0.38$

Summary

- We searched for SA in the galaxy distribution
- We found no evidence for SA in the LRG sample
- This confirms the WMAP anisotropy is not of primordial origin
- We constrain $-0.41 < g_* < +0.38$ with 95% confidence
- Looking ahead: future surveys (BigBOSS) may be able to constrain g_* another order of magnitude